
HAVE YOU HEARD? THEY DISCOVERED THE GOD PARTI...
IT'S CALLED THE HIGGS BOSON!

Theory Uncertainties for Higgs Couplings at CEPC

Sven Heinemeyer, IFT/IFCA (CSIC, Madrid/Santander)

Oxford, 04/2019

1. Motivation
2. The “easy” case: SM Higgs
3. The “difficult” case: BSM Higgs
4. Conclusions

1. Motivation

Experimental situation:

LHC/ILC/CLIC/FCC-ee/CEPC/. . .
will provide (high!) accuracy measurements!

Theory situation:

– Measurements are performed using theory predictions

– measured observables have to be compared with theoretical predictions (in various models: SM, MSSM, . . .)

Full uncertainty is given by the (linear) sum of experimental and theoretical uncertainties!

Some results shown here based on:
Write-up for FCC-ee physics WG2 – Precision EW Calculations

Theoretical uncertainties for electroweak and Higgs-boson precision measurements at the FCC-ee

Conveners: A. Freitas[1], S. Heinemeyer[2],
Contributors: M. Beneke[3], A. Blondel[4], A. Hoang[5], P. Janot[6], J. Reuter[7], C. Schwinn[8], and S. Weinzierl[9]

$\Rightarrow$ Here: taken as results for (general) high-luminosity e^+e^- collider

$\Rightarrow$ should be taken into account by "exp groups"!

$\Rightarrow$ Here: current status and future of Higgs(/EWPO) TH calculations
anticipated accuracy of Higgs(/EWPO) TH calc. in $\mathcal{O}(20)$ years

$\Rightarrow$ EWPO precision: talk by J. Gluza (yesterday)

Where we need theory prediction:

1. Prediction of the measured quantity
   Example: $\Gamma(H \to b\bar{b})$
   $\to$ at the same level or better as the experimental precision

2. Prediction of the measured process to extract the quantity
   Example: $e^+e^- \to ZH$
   $\to$ better than then "pure" experimental precision

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Two types of theory uncertainties:

1. intrinsic: missing higher orders

2. parametric: uncertainty due to exp. uncertainty in SM input parameters
   Example: m_t, m_b, α_s, $\Delta\alpha_{\text{had}}$, ...

Options for the evaluation of intrinsic uncertainties:

1. Determine all prefactors of a certain diagram class (couplings, group factors, multiplicities, mass ratios) and assume the loop is $\mathcal{O}(1)$

2. Take the known contribution at n-loop and $(n-1)$-loop and thus estimate the $n+1$-loop contribution:

$$\frac{(n+1)^{(\text{estimated})}}{n^{(\text{known})}} \approx \frac{n^{(\text{known})}}{(n-1)^{(\text{known})}}$$

   $\Rightarrow$ simplified example! Has to be done
   "coupling constant by coupling constant"

3. Variation of $\mu^{\overline{\text{MS}}}$ (QCD!, EW?)

4. Compare different renormalizations

2. The “easy” case: SM Higgs

Initial measurement: $\sigma \times$ BR

recoil method: $e^+e^- \to ZH$, $Z \to e^+e^-$, $\mu^+\mu^-$

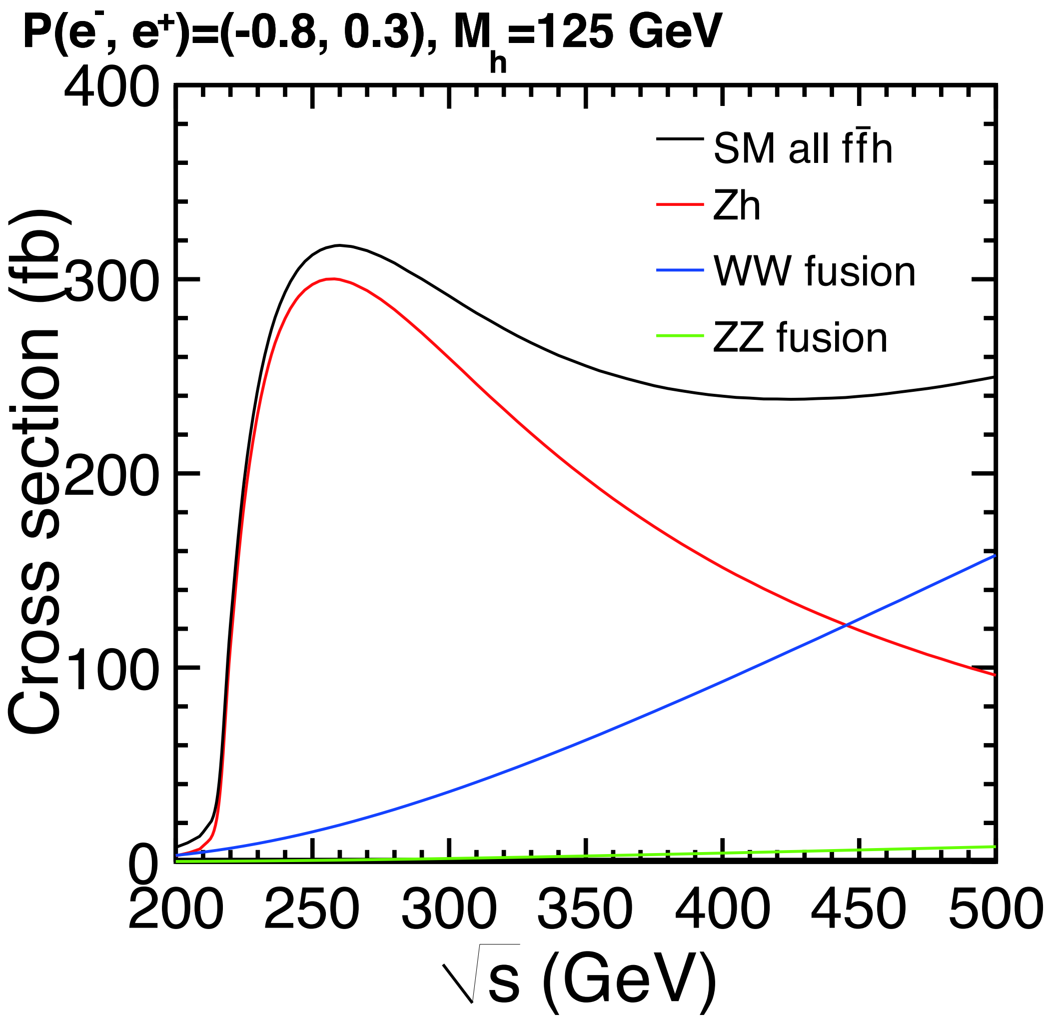
$\Rightarrow$ measurement of the Higgs production cross section

$\Rightarrow$ NO additional theoretical assumptions needed for absolute determination of partial widths

$\Rightarrow$ indirect measurement of total width

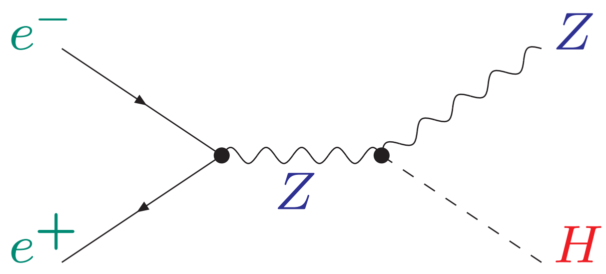
$\Rightarrow$ direct extraction of partial widths (couplings)

Higgs production cross sections:



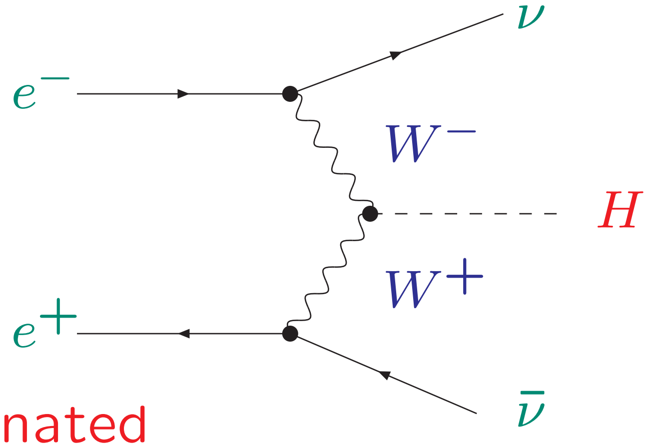
Higgs-strahlung:

$e^+e^- \to Z^* \to ZH$



weak boson fusion (WBF):

$e + e- \to \nu\bar{\nu}H$



CEPC: $\sqrt{s} \sim 250$ GeV, Higgs-strahlung dominated

$e^+e^- \to ZH$:

$\delta\sigma_{HZ}^{\text{exp}} \sim 0.4\%$

full one-loop available, corrections of 5-10%

rough estimate: $\delta\sigma_{HZ}^{\text{theo}} \sim 1\%$ from missing two-loop corrections

Two-loop corrections for $2 \to 2$ can in principle be done ...
$\mathcal{O}(\alpha_t\alpha_s)$ corrections: 1.3% [*Y. Gong, Z. Li, X. Xu, L. Yang '16*]

$\Rightarrow$ theory uncertainties sufficiently small
$\Rightarrow$ full two-loop for $2 \to 2$ should be done!

$e^+e^- \to \nu\bar{\nu}H$:

small contribution ...

Partial two-loop calculation (with closed fermion loops)
can in principle be done ...

$\Rightarrow$ theory uncertainties sufficiently small

Decay width theoretical uncertainties: General recipe:

[LHCHXSWG BR group '15]

1. Parametric Uncertainties: $p \pm \Delta p$
   - Evaluate partial widths and BRs with p, $p + \Delta p$, $p - \Delta p$ and take the differences w.r.t. central values
   - Upper $(p + \Delta p)$ and lower $(p - \Delta p)$ uncertainties summed in quadrature to obtain the Combined Parametric Uncertainty

2. Theoretical Uncertainties:
   - Calculate uncertainty for partial widths and corresponding BRs for each theoretical uncertainty
   - Combine the individual theoretical uncertainties linearly to obtain the Total Theoretical Uncertainty

   $\Rightarrow$ estimate based on "what is included in the codes"!

3. Total Uncertainty:

   Linear sum of the Combined Parametric Uncertainty and the Total Theoretical Uncertainties

Intrinsic uncertainties for decay widths:

"FCC-ee/CEPC" = expected precision on g^2_{Hxx}

Partial width	QCD	electroweak	total	future	FCC-ee/CEPC
$H \to b\bar{b}$	$\sim 0.2\%$	$< 0.3\%$	$< 0.4\%$	$\sim 0.2\%$	$\sim 1.0\%$
$H \to c\bar{c}$	$\sim 0.2\%$	$< 0.3\%$	$< 0.4\%$	$\sim 0.2\%$	$\sim 1.7\%$
$H \to \tau^+\tau^-$	–	$< 0.3\%$	$< 0.3\%$	$< 0.1\%$	$\sim 1.3\%$
$H \to \mu^+\mu^-$	–	$< 0.3\%$	$< 0.3\%$	$< 0.1\%$	$\sim 15\%$
$H \to gg$	$\sim 3\%$	$\sim 1\%$	$\sim 3.2\%$	$\sim 1\%$	$\sim 2\%$
$H \to \gamma\gamma$	$< 0.1\%$	$< 1\%$	$<1\%$	$< 1\%$	$\sim 3.6\%$
$H \to Z\gamma$	$\lesssim 0.1\%$	$\sim 5\%$	$\sim 5\%$	$\sim 1\%$	
$H \to WW \to 4f$	$< 0.5\%$	$< 0.3\%$	$\sim 0.5\%$	$\lesssim 0.4\%$	$\sim 0.5\%$
$H \to ZZ \to 4f$	$< 0.5\%$	$< 0.3\%$	$\sim 0.5\%$	$\lesssim 0.3\%$	$\sim 0.4\%$
Γ_{tot}				$\sim 0.3\%$	$\sim 1\%$

$\Rightarrow$ non-negligible for $H \to WW/ZZ \to 4f$

Future parametric uncertainties for decay widths:

decay	fut. intr.	fut. para. m_q	para. α_s	para. M_H	FCC-ee/CEPC
$H \to b\bar{b}$	$\sim 0.2\%$	0.6%	$< 0.1\%$	–	$\sim 1.0\%$
$H \to c\bar{c}$	$\sim 0.2\%$	$\sim 1\%$	$< 0.1\%$	–	$\sim 1.7\%$
$H \to \tau^+\tau^-$	$< 0.1\%$	–	–	–	$\sim 1.3\%$
$H \to \mu^+\mu^-$	$< 0.1\%$	–	–	–	$\sim 15\%$
$H \to gg$	$\sim 1\%$		0.5%	–	$\sim 2\%$
$H \to \gamma\gamma$	$< 1\%$	–	–	–	$\sim 3.6\%$
$H \to Z\gamma$	$\sim 1\%$	–	–	$\sim 0.1\%$	
$H \to WW$	$\lesssim 0.4\%$	–	–	$\sim 0.1\%$	$\sim 0.5\%$
$H \to ZZ$	$\lesssim 0.3\%$	–	–	$\sim 0.1\%$	$\sim 0.4\%$
$\Gamma_{\rm tot}$	$\sim 0.3\%$	$\sim 0.4\%$	$< 0.1\%$	$< 0.1\%$	$\sim 1\%$

$\Gamma_{\rm tot}$ applies "to all" (partial cancelations . . .)
$\Rightarrow$ non-negligible in particular for $H \to WW/ZZ \to$ 4f (δm_b optimistic?)

Future theory uncertainties?

Intrinsic uncertainties:

$H \to b\bar{b}, H \to c\bar{c}$: higher-order EW corrections ??

$H \to tau^+tau^-, H \to mu^+mu^-$: higher-order EW corrections ?

$H \to gg$: improvement difficult

$H \to \gamma\gamma$: already very precise . . .

$H \to Z\gamma$: EW corrections could help . . .

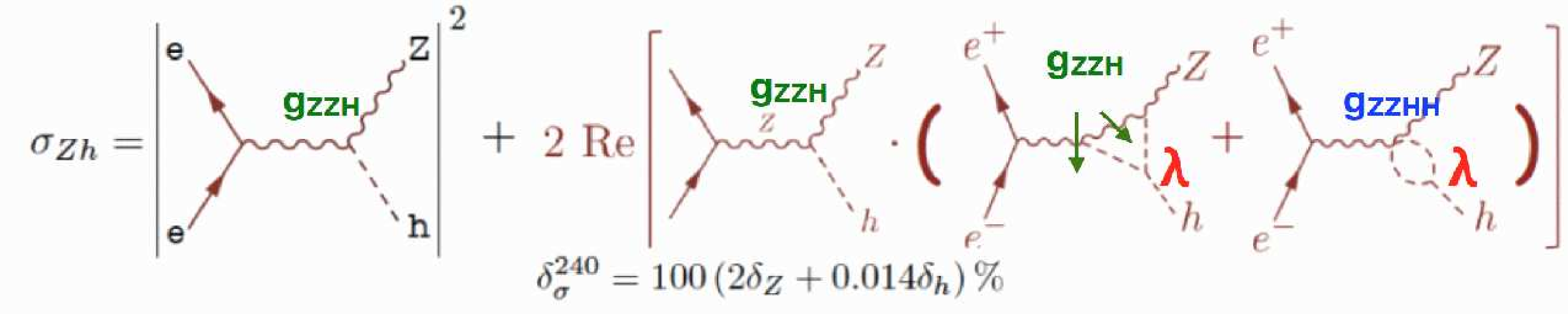
$H \to WW^{(*)}, H \to ZZ^{(*)}$: already very precise, two-loop corrections unclear

$\Rightarrow$ intrinsic uncertainty can/will be sufficiently under control?!

Parametric uncertainties:

- largely driven by $\delta m_b \Rightarrow$ improvement unclear (to me)
  lattice community does not seem to agree
- some improvement in α_s possible

Higgs self-coupling from loop corrections? [arXiv:1312.3322]



⇒ sensitivity to λ_{HHH} goes down for higher $\sqrt{s}$

⇒ percent precision possible on σ_{ZH}, λ_{HHH}

⇒ indirect and model dependent measurement
(to be included in a global coupling fit - within a model)

⇒ $\mathcal{O}\,(10\%)$ measurement of λ_{HHH} needed
to measure σ_{HZ} at the percent level!

⇒ higher $\sqrt{s}$ needed!

One word of caution:

The above numbers have all been obtained assuming the SM as calculational framework.

The SM constitutes the model in which highest theoretical precision for the predictions of EWPO can be obtained.

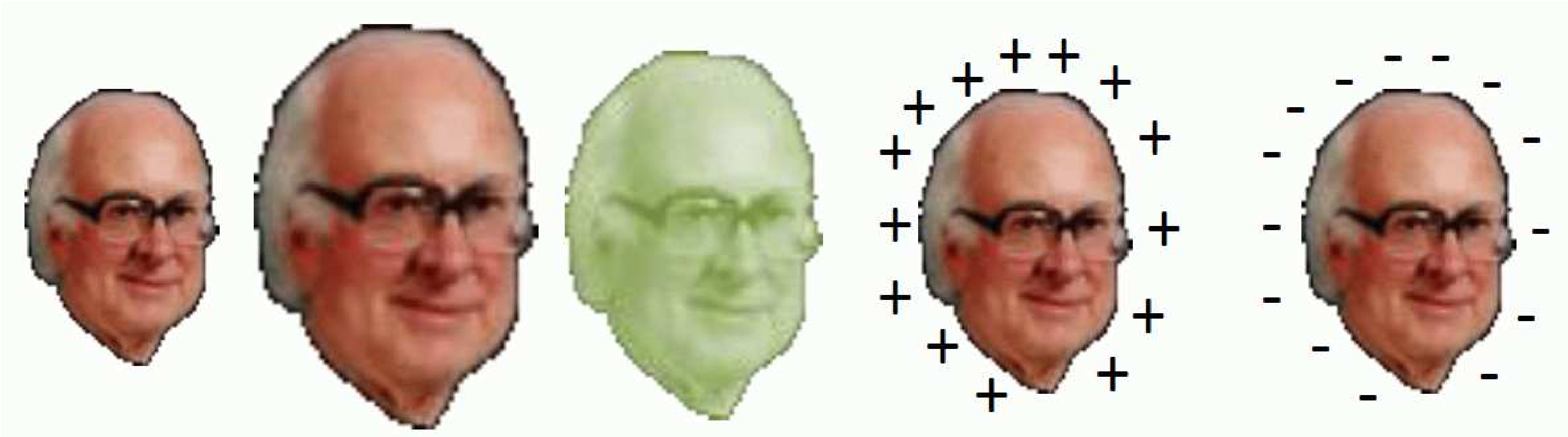
We know that BSM physics must exist! (DM, gravity, . . .)

As soon as BSM physics will be discovered, an evaluation of the Higgs predictions in any preferred BSM model will be necessary.

The corresponding theory uncertainties, both intrinsic and parametric, can then be larger (as known for the MSSM).

A dedicated theory effort (beyond the SM) would be needed in this case.

3. The “difficult” case: BSM Higgs



Required precision for Higgs couplings?

MSSM example:

$$\kappa_V \approx 1 - 0.5\% \left(\frac{400\ \text{GeV}}{M_A}\right)^4$$

$$\kappa_t = \kappa_c \approx 1 - \mathcal{O}(10\%) \left(\frac{400\ \text{GeV}}{M_A}\right)^2 \cot^2\beta$$

$$\kappa_b = \kappa_\tau \approx 1 + \mathcal{O}(10\%) \left(\frac{400\ \text{GeV}}{M_A}\right)^2$$

Composite Higgs example:

$$\kappa_V \approx 1 - 3\% \left(\frac{1\ \text{TeV}}{f}\right)^2$$

$$\kappa_F \approx 1 - (3-9)\% \left(\frac{1\ \text{TeV}}{f}\right)^2$$

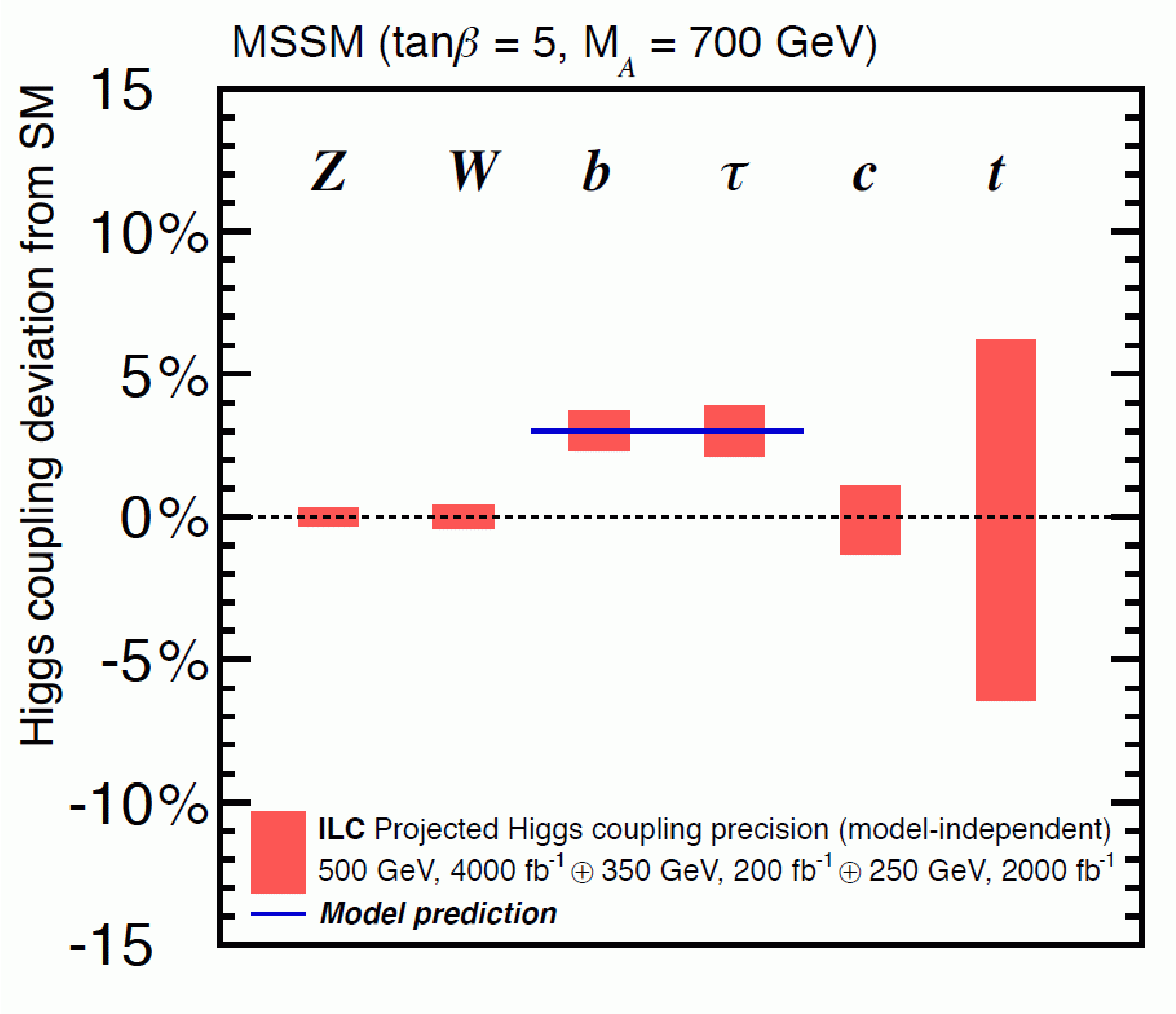
$\Rightarrow$ couplings to bosons in the per mille range

$\Rightarrow$ couplings to fermions in the per cent range

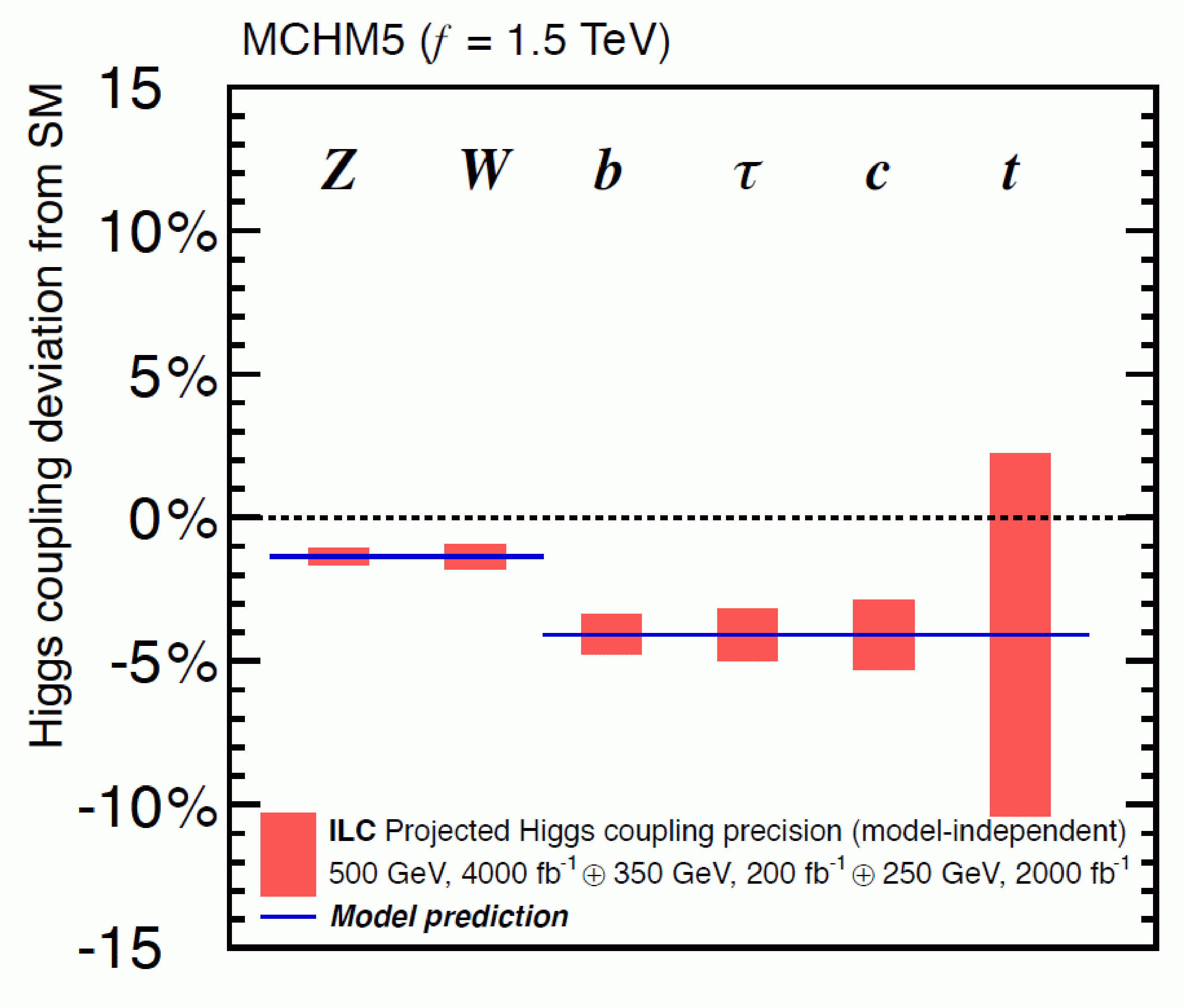
$\Rightarrow$ the more precise the better

$\Rightarrow$ theory match?

ILC precision vs. MSSM prediction:



ILC precision vs. Composite Higgs prediction:



Required precision for $\mathcal{CP}$-admixture?

$$\boxed{H = \cos\alpha\ \mathcal{CP}\text{-even} + \sin\alpha\ \mathcal{CP}\text{-odd}}$$

$$\mathcal{A}(X \to VV) = \frac{1}{v}\left(a_1 m_V^2 \varepsilon_1^* \varepsilon_2^* + a_2 f_{\mu\nu}^{*(1)} f^{*(2),\mu\nu} + a_3 f_{\mu\nu}^{*(1)} \tilde{f}^{*(2),\mu\nu}\right)$$

$$\mathcal{A}(X \to f\bar{f}) = \frac{m_f}{v} \bar{u}_2 \left(b_1 + i b_2 \gamma_5\right) u_1$$

$$f_{\mathcal{CP}} = \frac{|a_3|^2 \sigma_3}{\sum |a_i|^2 \sigma_i}$$

Desired precision:

gauge bosons: $f_{\mathcal{CP}} \lesssim 10^{-5}$ (loop suppressed)

fermions: $f_{\mathcal{CP}} \lesssim 10^{-2}$

Taking the MSSM Higgs production as show case:

$\Rightarrow$ "best case" of "difficult case"!

Neutral Higgs production:

$$e^+e^- \to h_i Z,\ h_i\gamma,\ h_i h_j,\ h_i\nu\bar{\nu},\ h_i e^+e^-,\ h_i t\bar{t},\ h_i b\bar{b},\ \ldots \qquad (i,j = 1,2,3)\,.$$

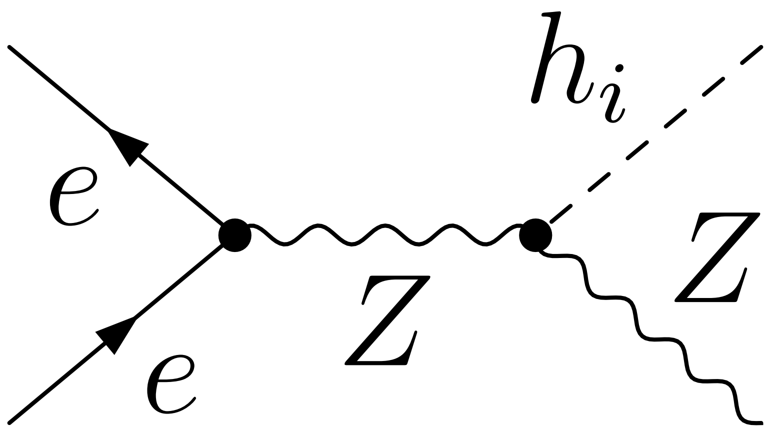
Now available in the cMSSM at the full one-loop level:
[*S.H., C. Schappacher '15*] [*F. Arco, S.H., C. Schappacher '18*]

$$\sigma(e^+e^- \to h_i h_j)$$
$$\sigma(e^+e^- \to h_i Z)$$
$$\sigma(e^+e^- \to h_i \gamma)$$

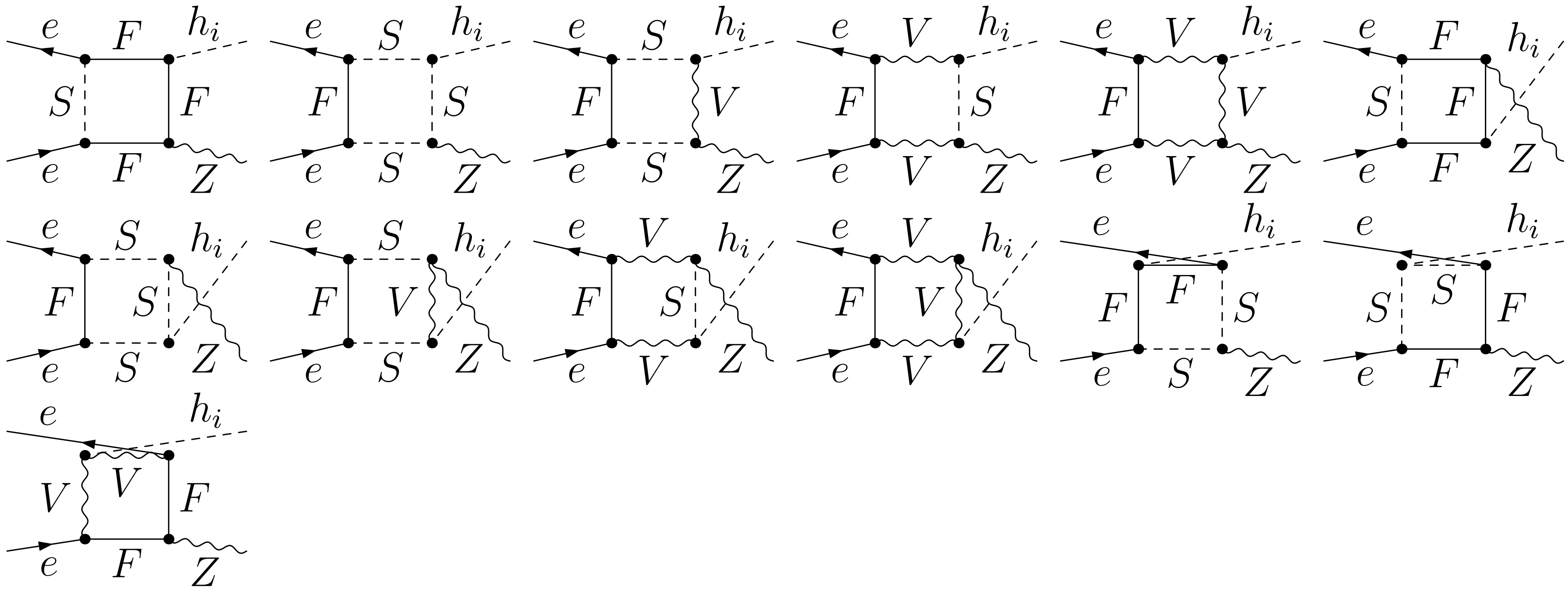
$\Rightarrow$ no dedicated two-loop corrections available yet
$\Rightarrow$ as in SM full two-loop would be needed (possible . . .)

Remember: more neutral Higgs production channels
$\oplus$ charged Higgs production channels!

$e^+e^- \to h_i Z$:



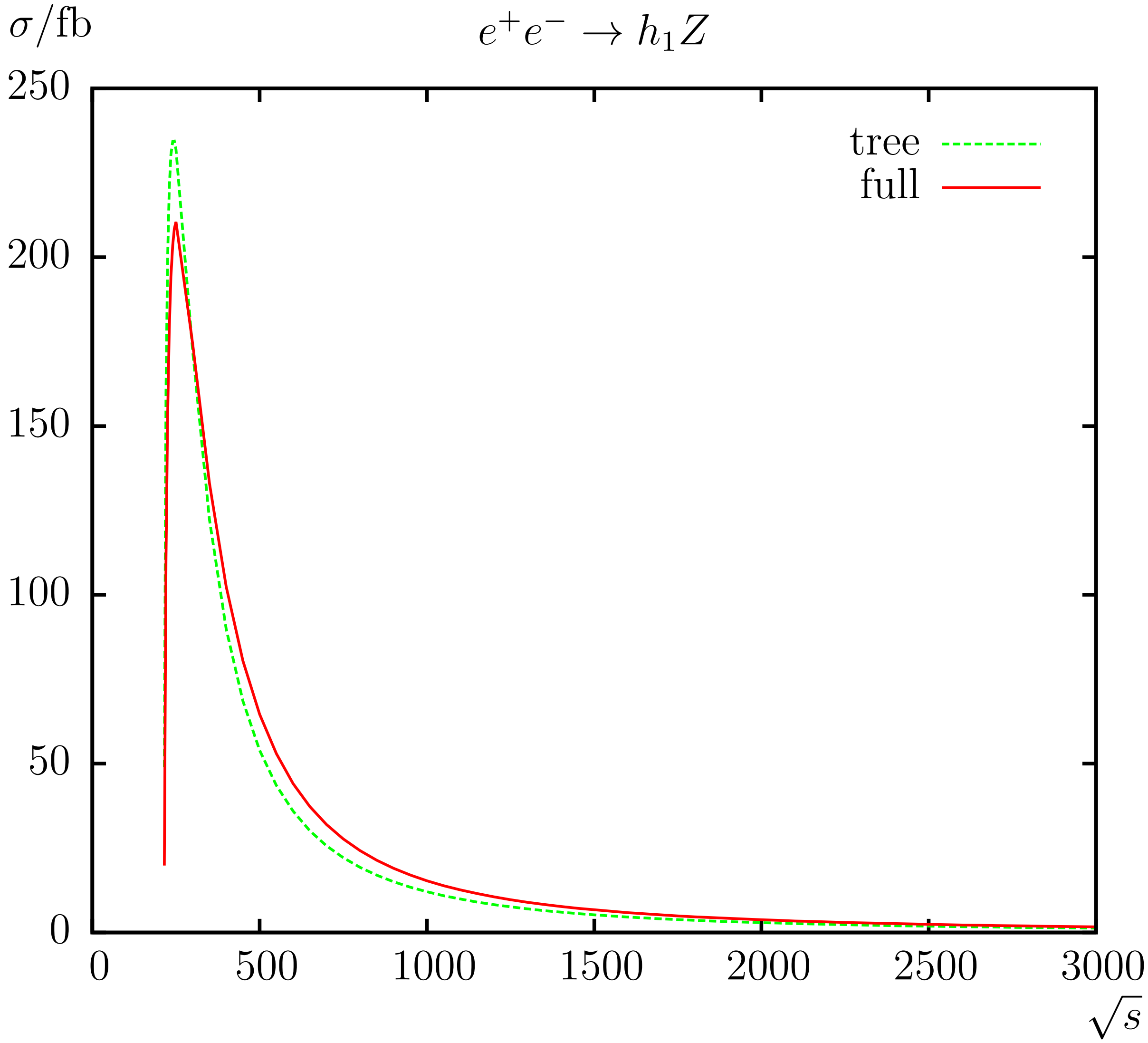
h_i
e
e
Z
Z



e F h_i S F e F Z
e S h_i F S e S Z
e S h_i F V e S Z
e V h_i F S e V Z
e V h_i F V e V Z
e F h_i S F e F Z
e S h_i F S e S Z
e S h_i F V e S Z
e V h_i F S e V Z
e V h_i F V e V Z
e h_i F F S e S Z
e h_i S S F e F Z
e h_i V V F e F Z

$e^+e^- \to h_1 Z$ (CEPC $\to$ CLIC):

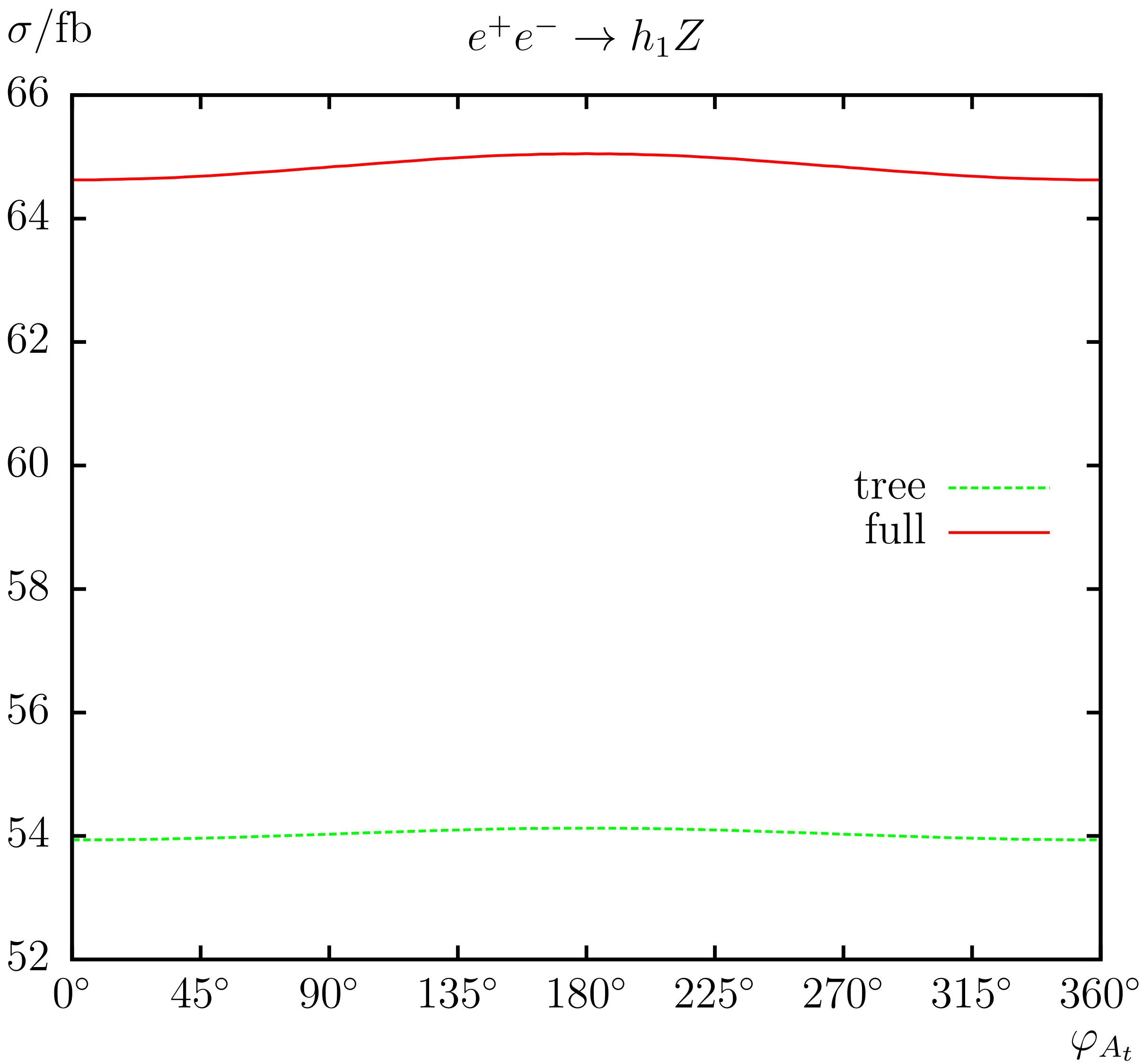
[S.H., C. Schappacher '16]



$\Rightarrow$ loop corrections crucial $\Rightarrow$ two-loop required

$e^+e^- \to h_1 Z$: effects of complex parameter

[S.H., C. Schappacher '16]



$\Rightarrow$ complex parameters have per-cent effects, has to be included!

Most complete implementation in cMSSM: FeynHiggs

Evaluation of all MSSM Higgs boson masses and mixing angles

- $M_{h_1}, M_{h_2}, M_{h_3}, M_{H^\pm}$, α_{eff}, $\mathbf{Z}_{ij}$, $\mathbf{U}_{ij}$, . . .

Evaluation of all neutral MSSM Higgs boson decay channels (so far)

- total decay width Γ_{tot}
- $\text{BR}(h_i \to f\bar{f})$: decay to SM fermions: full 1L, running m_q at 3L, $\mathbf{Z}_{ij}$
- $\text{BR}(h_i \to Z^{(*)}Z^{(*)}, W^{(*)}W^{(*)})$: decay to massive SM gauge bosons: Prophecy4f $\oplus$ coupling factors, $\mathbf{U}_{ij}$
- $\text{BR}(h_i \to \gamma\gamma, gg)$: decay to massless SM gauge bosons: NLO QCD, gg: NNLO, NNLL from SM, $\mathbf{U}_{ij}$
- $\text{BR}(h_i \to h_j Z^{(*)}, h_j h_k)$: decay to gauge and Higgs bosons: $h_j Z^{(*)}$: $\mathbf{U}_{ij}$, $h_j h_k$: full 1L, log-resum, $\mathbf{Z}_{ij}$
- $\text{BR}(h_i \to \tilde{f}_i \tilde{f}_j)$: decay to sfermions: $\mathbf{U}_{ij}$
- $\text{BR}(h_i \to \tilde{\chi}^\pm_i \tilde{\chi}^\mp_j, \tilde{\chi}^0_i \tilde{\chi}^0_j)$: decay to charginos, neutralinos: $\mathbf{U}_{ij}$

Overall (N)MSSM Higgs decay intrinsic uncertainty estimates

[*F. Domingo, S.H., S. Passehr, G. Weiglein '18*]

- $h_i \to q\bar{q}$: SM-like: SM NNLO QCD, EW NNLO, SUSY 2L: $\sim 5\%$
  heavy: as SM-like, Sudakov logs: $\sim 5 - 10\%$
- $h_i \to \ell\bar{\ell}$: SM-like: $\lesssim 1\%$
  heavy: Sudakov logs for very heavy Higgses $\lesssim 10\%$
- $h_i \to WW^{(*)}, ZZ^{(*)}$: SM-like: $\lesssim 1\%$
  heavy: missing 2L (very small width): $\lesssim 50\%$
- $h_i \to \gamma\gamma, gg, \gamma Z$: $\gamma\gamma$: NNLO QCD, EW: $\lesssim 4\%$
  gg: NNLO QCD, EW: $\lesssim 4\%$
  γZ: NLO: $\sim 5\%$
- $h_i \to$ SUSY SUSY: [*S.H., C. Schappacher '14-'16*]
  1L effects $10 - 20\%$, 2L?
- all decays: $\mathbf{U}_{ij}$, $\mathbf{Z}_{ij}$: few %, effects close to threshold?

$\Rightarrow$ approaching CEPC precision for SM-like Higgs
(not for heavy Higgses yet)

4. Conclusions

- High anticipated experimental precision for Higgs/EWPO at future e^+e^- colliders

- Crucial: theory uncertainties: intrinsic and parametric

$$\text{total} = \sqrt{\text{experimental}^2 + \text{parametric}^2} + \text{intrinsic}$$

- We give (realistic/optimistic) estimates for future intrinsic and parametric uncertainties

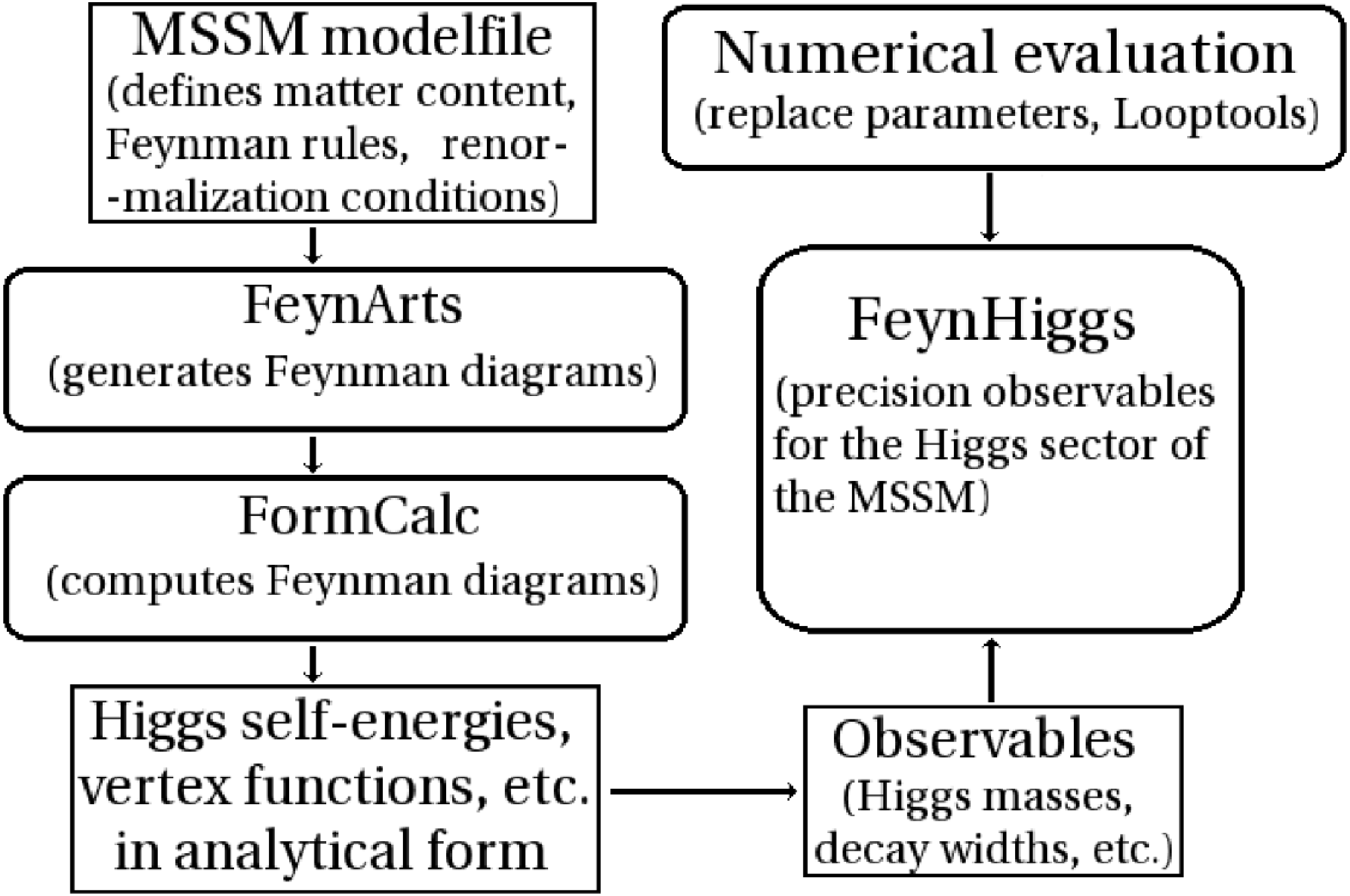
- SM Higgs: cross section can be under control with full $2 \to 2$ calc.
  intrinsic unc. can be relevant for $H \to WW/ZZ \to$ 4f
  parametric unc. can be relevant, in particular for $H \to WW/ZZ \to$ 4f

- BSM Higgs: deviations in per-cent range expected
  $\Rightarrow$ MSSM is "best case" of "difficult case"!
  cross sections can be under control with full $2 \to 2$ calc.
  intrinsic unc. approaching CEPC precision for SM-like Higgs
  not for heavy Higgses yet
  parametric unc. at least as large as in SM

- Uncertainties should be taken into account by experimental analyses!


Further Questions?

FeynHiggs "workflow" :



Idea for this work:

[*slide from F. Domingo*]

- Renormalization of the CP-conserving Higgs-sector
  [Drechsel, Galeta, Heinemeyer, Weiglein, (2016)];
- CP-violating NMSSM, on-shell neutral Higgs *[Drechsel, F.D., Paßehr (2017)]*;
- Neutral Higgs decays into SM particles at full one-loop order
  [F.D., Heinemeyer, Paßehr, Weiglein, (2018)];
- Higgs-to-Higgs + Higgs-to-SUSY on-going...
- Inclusion within FeynHiggs in an unforseeable future...

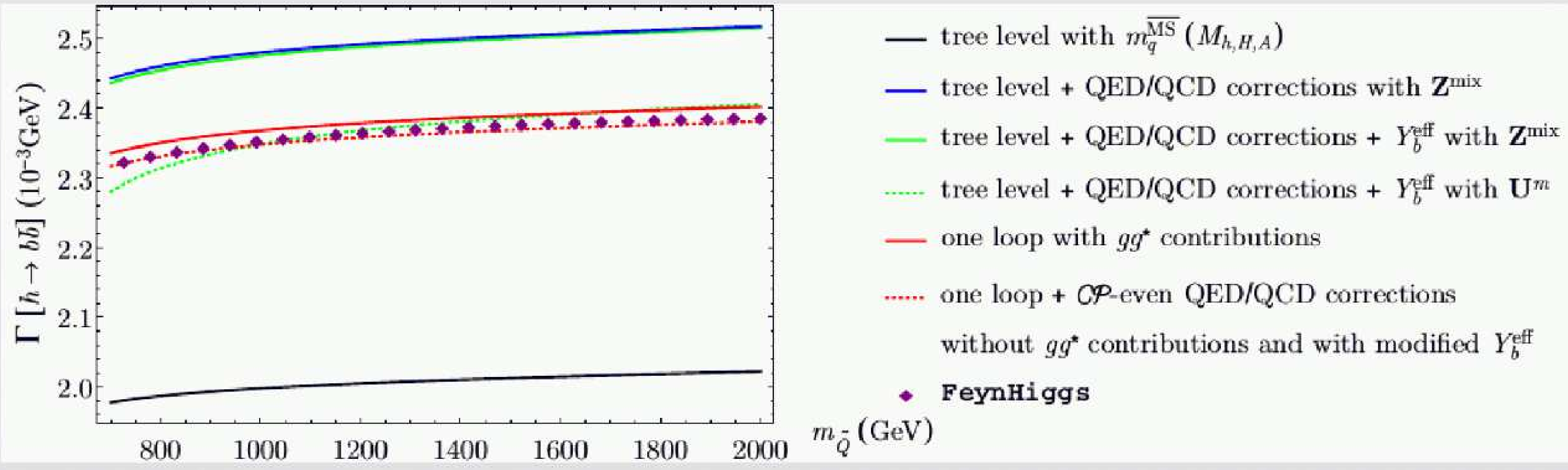
Learn from MSSM and adapt to the NMSSM.
+ Re-juvenate MSSM from NMSSM.

In the future: **FeynHiggs 3.0**

$\Rightarrow$ few numerical examples for the Higgs decays

Bringing the NMSSM to the same level: NMSSM in the MSSM limit

[*slide from F. Domingo*]

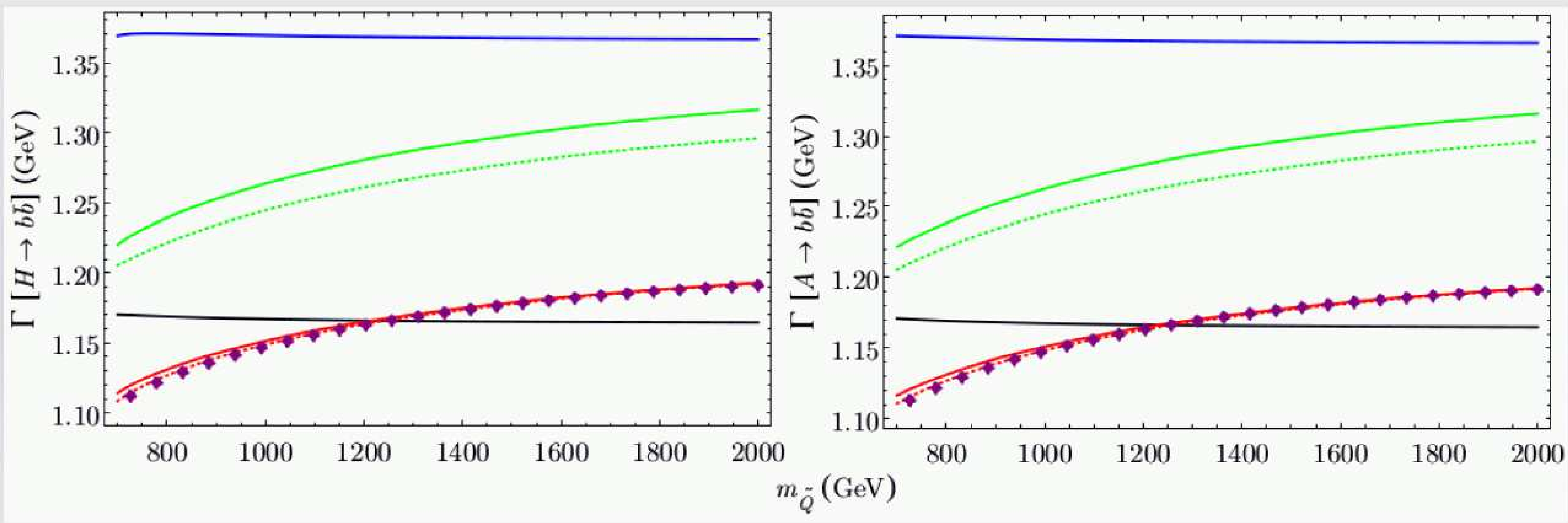


SM-like Higgs state

- Radiative corrections dominated by QCD-corrections;
- Unitary tree-level approximation works well;
- Difference wrt. FH (small): $h \to g(g^* \to b\bar{b})$
  (whether $h \to b\bar{b}$ or $h \to gg$ is an experimental question).

Bringing the NMSSM to the same level: NMSSM in the MSSM limit

[*slide from F. Domingo*]

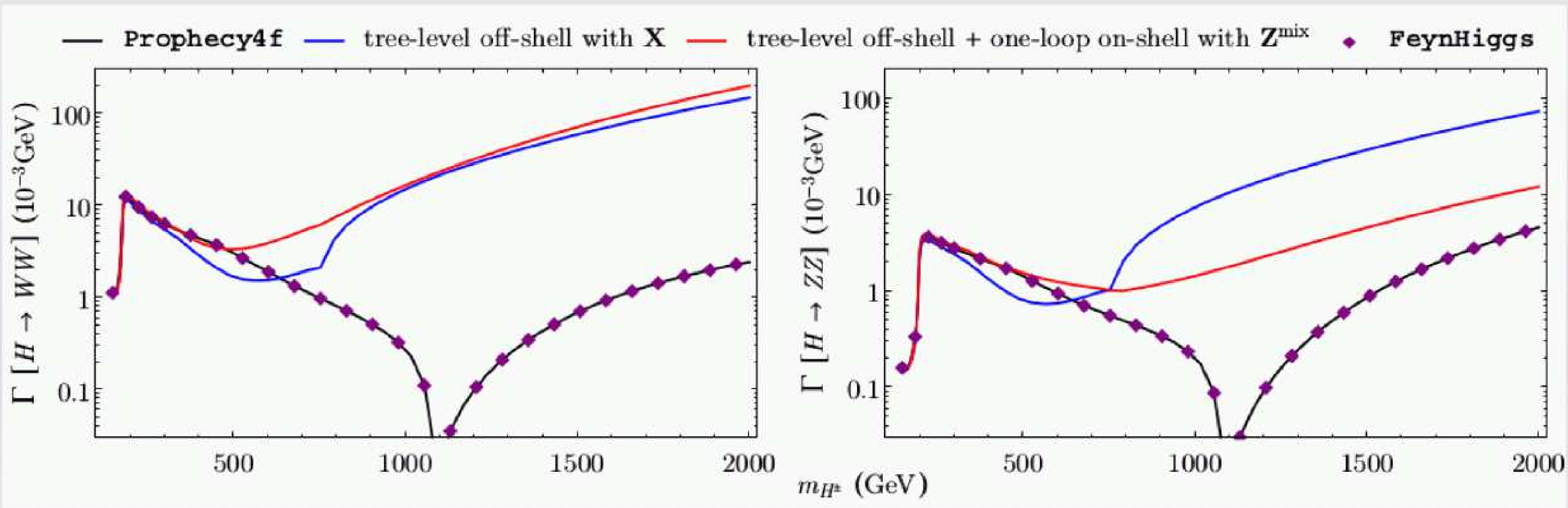


Heavy doublet Higgs states at ~ 1 TeV

- Sizable EW corrections due to Sudakov logarithms;
- Unitary tree-level approximation 'fails' ~ 10% off;
- Difference wrt. FH (minor): UV scale in Δ_b (higher-order).

Bringing the NMSSM to the same level: NMSSM in the MSSM limit

[*slide from F. Domingo*]

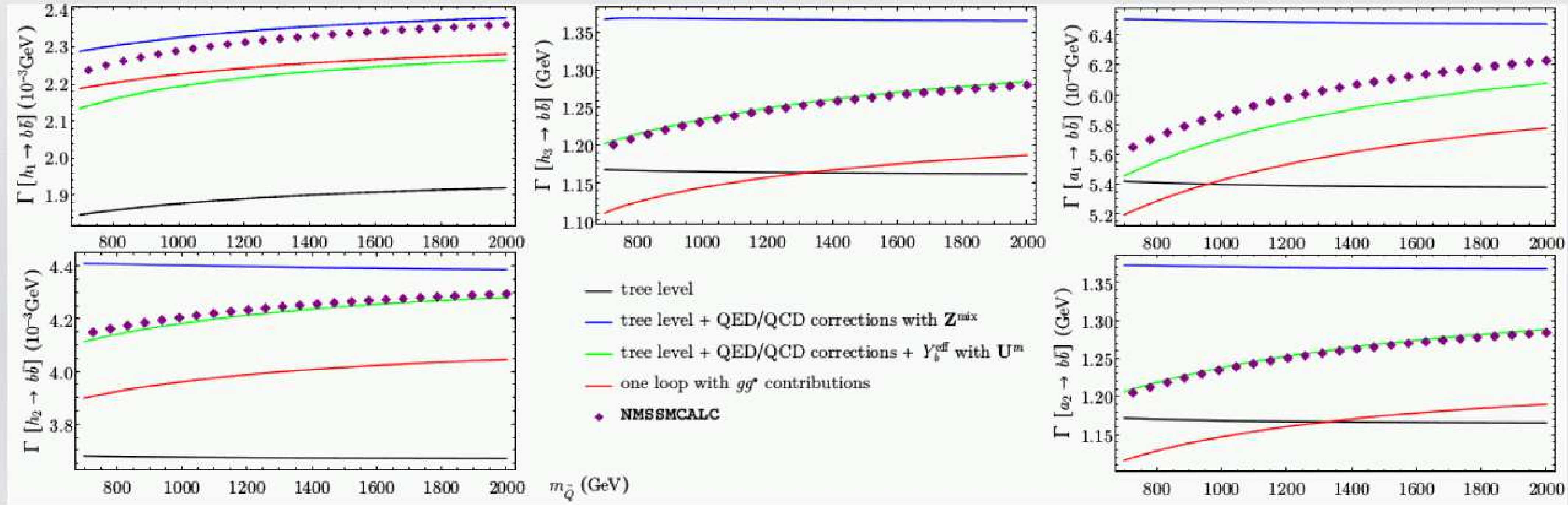


Heavy CP-even doublet Higgs state

- black curve: SM 1L prediction of Prophecy4f rescaled (as FH);
- Red curve: full one-loop (on-shell);
- Rescaling procedure fails for a decoupling state $g^{HVV}/g^{H_{SM}VV} \simeq 0$.

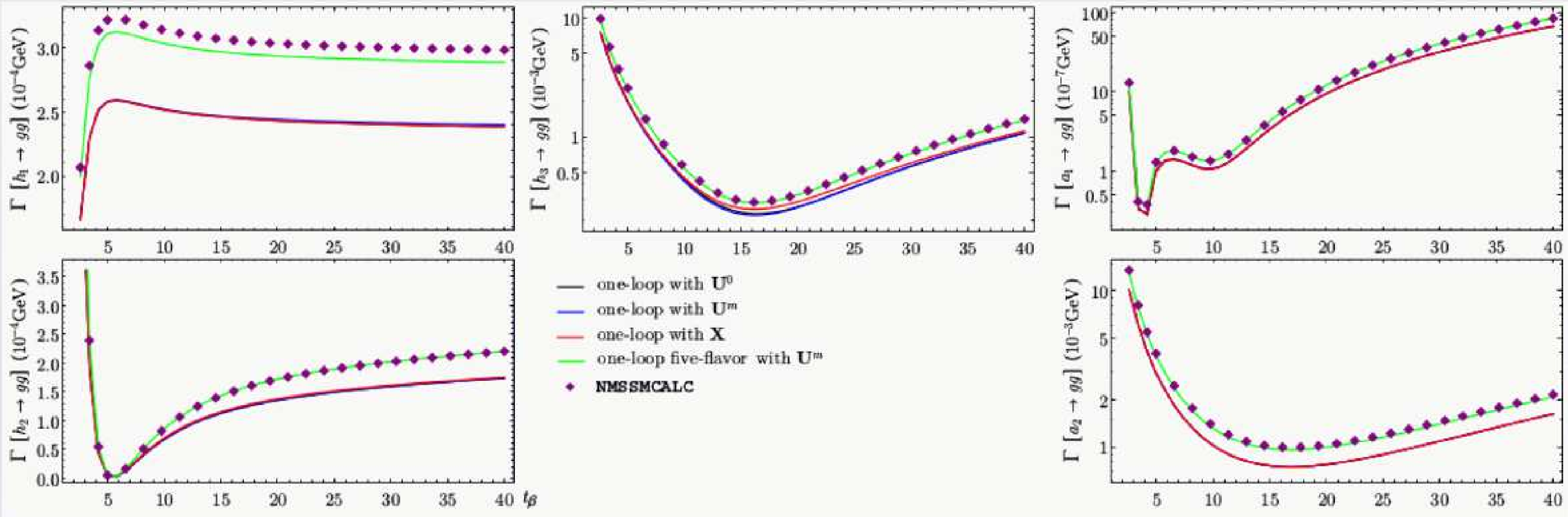
Bringing the NMSSM to the same level: NMSSM

[*slide from F. Domingo*]



- HDECAY provides a QCD/large $\tan\beta$-corrected width (including SQCD) $\simeq$ our green line;
- Full one-loop shows EW Sudakov logarithms for heavy states.

Here: h_1 SM-like; h_2 (640 GeV) and a_1 (320 GeV) singlet-like; h_3 and a_2 doublet-like (1 TeV).



- HDECAY performs at the same order as us with 5-flavor radiation;
- $\sim 4\%$ deviation due to normalization factor (difference of EW 2-loop and QCD 3-loop order).

Here: h_1 SM-like; h_2 (650 GeV) and a_1 (320 GeV) singlet-like; h_3 and a_2 doublet-like (1 TeV).